OPTICAL IDENTIFICATION OF THE X-RAY BURSTER IN THE GLOBULAR CLUSTER NGC1851[1]

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ABSTRACT

We have obtained exposures of the field of X 0512-401 in the globular cluster NGC1851, in X-rays with the *Chandra X-ray Observatory*, and in the far-UV with the *Hubble Space Telescope*. We derive an accurate new X-ray position (within $\sim 1''$) for X 0512-401, which enables us to confirm that the *only* plausible candidate for the optical/UV counterpart is the Star A, which we previously identified from WFPC2 imaging. We find no evidence for X-ray or UV flux modulation on the ultra-short ($\lesssim 1$ hr) expected binary period, which implies a low system inclination. In addition, we have detected and spatially resolved an X-ray burst event, confirming the association of the burster, quiescent X-ray source, and optical object. The very large L_X/L_{opt} of this object implies an extraordinarily compact system, similar to the sources in NGC6624 and NGC6712.

Subject headings: globular clusters: individual (NGC1851) – stars: neutron – ultraviolet: stars – X-rays: stars – X-rays: bursts

1. INTRODUCTION

The nature of the 12 bright ($>10^{36}$ erg s^{-1}) X-ray sources in globular clusters (see e.g. Verbunt et al. 1995; Bailyn 1996) appears distinct from that of low-mass X-ray binaries (LMXBs) in the Galaxy as a whole. That they are LMXBs was established by mass estimates based on their cluster positions, as measured by the *Einstein*/HRI (Grindlay et al. 1984). However, they are overabundant by a factor $\sim$100 requiring entirely different formation mechanisms (see Verbunt 1988). Moreover, studies of the limited number of optical counterparts (Deutsch 1998; Deutsch et al. 2000) imply that their period distribution is also remarkably different from that of field LMXBs, with a preponderance of ultra-short period systems. NGC 6624 harbors the shortest period binary system known (with $P \simeq$ 11min), and our *HST* observations of the X-ray source in NGC 6712 (Homer et al. 1996) indicated that it too is likely to be a similarly exotic system. Indeed, the only companion to the neutron star primary that can fit into such a compact binary is a white dwarf, making them double degenerates– remarkable end-points to binary stellar evolution.

Even given the $3''$ (90% confidence limit) *Einstein* X-ray positions, optical identifications are very difficult, due to the extremely crowded locations. In the case of NGC 1851, Deutsch et al. (1998) WFPC2 imaging revealed $\sim$300

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stars within the *Einstein* error circle. Their proposed counterpart, Star A, is a very strong candidate, given its similarity in color (faintness and large UV-excess) to the confirmed counterpart in NGC6712, yet a ∼5% *a posteriori* probability still remained that such a UV-excess star could coincidentally lie within the *Einstein* X-ray error circle. Furthermore, earlier ground-based work by Aurière et al. (1994) suggested that another UV-bright object with colors of a horizontal branch star, X1, might be an unusual counterpart. Clearly, additional observations were needed to confirm or refute these various suggested identifications.

To that end, we have obtained both *Chandra*/HRC data of the field in order to significantly improve the X-ray position, and a set of time resolved *HST*/STIS FUV-images to search for any variability. We present the results of these observations in this Letter.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Chandra X-ray Observatory*

Chandra observed the field of X 0512-401 for 12ks on 1999 December 25. The high resolution camera + low-energy transmission grating spectrograph mode (HRC-S+ LETG; Murray et al. 1997; Brinkmann et al. 1997; Predehl et al. 1997) we chose provides the highest possible spatial resolution available from *Chandra*, to achieve our primary science goal, but also a high resolution low energy spectrum of the bright source. The spectral results will be presented elsewhere, whilst we will concentrate on the positional result here.

Data reduction was initially undertaken with routines in `CIAO v1.1.5`. The anti-coincidence shield of HRC-S is not operational, owing to a timing error in the electronics. This leads to a much higher background rate of (false) events. However, the intrinsic energy resolution of the detector (though poor) can be used to easily remove 25% of this by excluding the highest energy channel. A sliding-cell detection routine (`tgdetect`) confirmed that only the one source was strongly detected, the LMXB, and also centroided its position to within 0.03″ (0.2 pix). A lightcurve was also extracted using all available data. Regions were defined covering the 0th and 1st order images, and 4 rectangular background regions above and below. The events were then summed into 2s bins, the background scaled and lastly subtracted using the `CIAO` routine `lightcurve`.

2.2. *Hubble Space Telescope*

Four orbits (∼12 ks) of *HST*/STIS (Kimble et al. 1998) imaging were undertaken on 1999 March 24. We used the FUV MAMA with the long-pass quartz filter in time-tag mode, to provide complete flexibility for temporal analysis. Its 25″ × 25″ field of view covered both the cluster core and the entire *Einstein* X-ray error circle. In this ∼1400Å–1700Å passband even the core of the globular cluster is uncrowded (see fig. 1, lower left), and we found that 0.2″ radius aperture photometry worked best (optimized according to a curve of growth analysis). To limit systematic effects we applied differential photometry, whereby the magnitudes of the stars of interest were calculated relative to an ensemble of the brightest stars in the field.

3. REFINING THE X-RAY POSITION

Although the superlative PSF of *Chandra* enables a very precise determination of a relative position for the X-ray source, we require an absolute value. Unfortunately, the lack of other bright X-ray sources in the field means that we cannot derive a precise absolute position by correcting relative to known positions. Instead, we rely on the calibration of the observatory's aspect. The *Chandra* team has made a detailed study of the aspect behaviour, based on comparisons between the X-ray positions of all sources with identifications and precise positions in the optical/radio, specifically objects appearing in the Hipparcos/Tycho-2 (Perryman et al. 1997; Høg et al. 2000), USNO A-2 (Monet 1998) and ICRF (Ma et al. 1998) catalogs. This has revealed a long-term drift in the aspect of each of the detector systems, although only 10 data points are available for HRC-S observations to date. We were provided with the appropriate corrections (from a linear fit) for the date of our observation. For all detectors combined the residuals then have an rms of 0.6″, whilst for the HRC-S subset the value is slightly larger, 0.7″. We adopt this latter value as an estimate of the intrinsic aspect uncertainty.

Table 1: X-ray and optical/UV positions in the ICRS.

Source of Positions	No. of matches	Δ(RA) (seconds)	Δ(DEC) (arcsecs)	Source positions RA(2000)	DEC(2000)	Dataset
Chandra Aspect				5:14:6.43	-40:02:37.63	*Chandra* X-ray
USNO A-2	267	-0.02 ± 0.01	-0.16 ± 0.13	5:14:6.41	-40:02:38.22	*HST* optical/UV
Tycho-2	36	-0.01 ± 0.02	-0.33 ± 0.33	5:14:6.42	-40:02:38.05	*HST* optical/UV

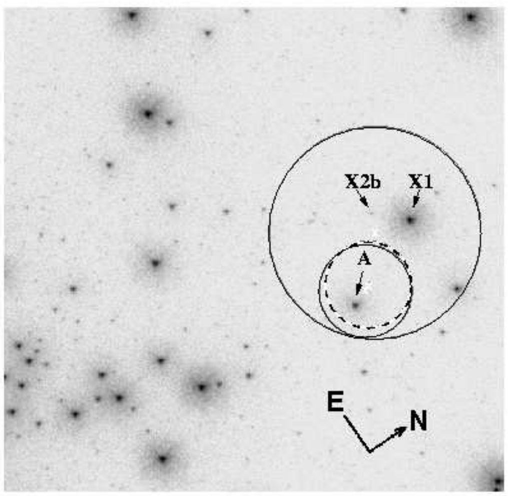

Fig. 1.— Deep (13ks) *HST*/STIS FUV image of the core of NGC1851. The large error circle (3″ radius) is that of the *Einstein*/HRI X-ray position. The two smaller circles indicate the major refinement afforded by *Chandra*/HRC-S, and show that using either the Tycho-2 (solid) or USNO A-2 (dashed) catalogs to calculate the offset to the *HST* Guide star catalog makes no significant difference: both include Star A, whilst excluding all other UV-bright objects. All circles represent 90% confidence.

Before we can overlay our X-ray position onto the *HST*/FUV image, a final correction must be made for different frames of reference. Essentially the FUV image can be tied directly to the *B* band images used by Deutsch et al. (1998), upon which accurate astrometry was performed to derive the optical positions of the various stars of interest within the *Einstein* error circle[2]. However, this astrometry made use of the then current *HST* Guide star catalog (HST-GSC; Jenkner et al. 1990), which predates the adoption of the International Celestial Reference System (ICRS; Feissel and Arias 1997), in which the Hipparcos/Tycho, USNO A-2 and ICRF catalog are grounded. Hence, we have calculated the offsets between HST-GSC and ICRS by matching stars appearing in both HST-GSC and either Tycho-2 or USNO A-2 within 6′–30′ of the position of X 0512-401 (thereby excluding the crowded regions at the globular cluster center). The results are given in Table 1. For clarity we combine the rms uncertainty in this final frame offset with the *Chandra* positional uncertainty, yielding 90% error radii of 1.3″ and 1.2″ for Tycho-2 and USNO A-2 offsetting respectively. In both cases, the *Chandra* X-ray position area is reduced by a factor of 6 from the *Einstein* result, and as shown in figure 1, the Deutsch et al. (1998) candidate Star A still lies squarely within. We can also now finally exclude X1 (Aurière et al. 1994) at the 99.9% confidence level. Star A is in fact the *only* UV bright object visible within the *Chandra* error circle, and the probability of a chance alignment has been reduced to $\lesssim 1\%$ following the arguments of Deutsch et al. (1998).

4. X-RAY/FUV VARIABILITY

Globular cluster X-ray sources are thought to essentially all be X-ray bursters. Despite the very high quiescent X-ray flux of this source, there appears to be only one previously-published X-ray burst, observed a quarter-century ago from *Uhuru*

[2]We are able to confirm the identity of the FUV star with Star A on the basis of its spectral energy distribution. The MAMA flux measure of $8.7 \pm 0.4 \times 10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ is fully consistent with the previous FOS and WFPC2 results.

(Forman and Jones 1976), obviously with very limited angular resolution. Our *Chandra* observations fortuitously observe and spatially resolve an X-ray burst (Figure 2). We thus can now definitively associate the quiescent X-ray source X0512-401, the X-ray burster, and the optical counterpart.

We have also searched for variability in the persistent X-ray emission, but find none, setting a 99% confidence upper limit of 4% on the semi-amplitude of any periodic modulation between 1 min and 1.5 hr (after subtraction of a 385s sinusoid, an artifact of dithering).

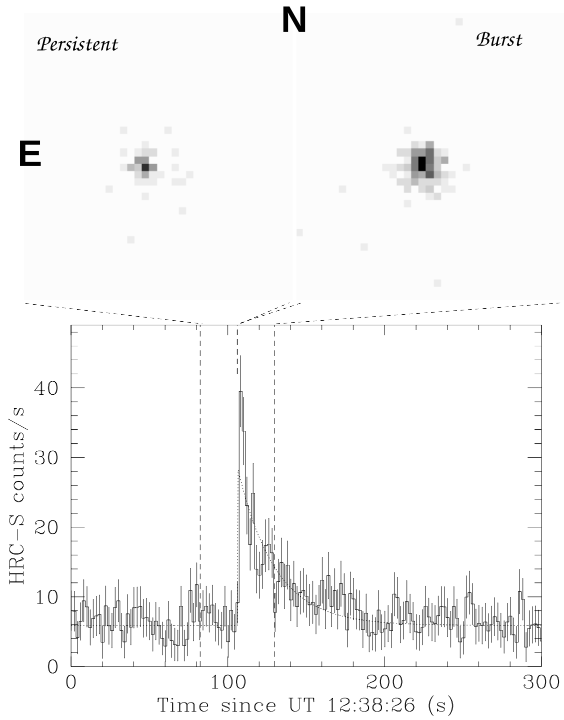

Fig. 2.— Upper panel: X 0512-401 in NGC1851 imaged by *Chandra*/HRC-S immediately prior to and during the peak of an X-ray burst event. Each image is a 23.6s exposure corresponding to one e-folding time of the exponential burst decay. Lower panel: Lightcurve detail with 2 s binning showing the flux evolution of the burst. The fit to a fast-rise exponential decay model is over-plotted. The decay time is consistent with the only other published result, from *Uhuru*.

Interestingly, our results on the FUV variability are equally null. As expected Star X1 appears to be a constant source (upper limit of 2.4%), but so does Star A. The limit on Star A of 5% on the semi-amplitude flux modulation between 5 min and 6 hr provides a significant constraint. For comparison, the measured UV modulation semi-amplitudes for the sources in NGC6624 and NGC6712 are ∼8% and ∼4% respectively (Anderson et al. 1997; Homer et al. 1996). The assumption that any UV modulation would arise from the varying contribution of the X-ray heated donor star's face implies a low inclination ($\lesssim 30°$) for the NGC1851 system. Lastly, we also checked for any burst events in the reprocessed UV flux, but again we found nothing.

5. CONCLUSIONS

Our *Chandra* observations confirm the bursting nature of, and provide a new precise and accurate X-ray position for, the luminous source X 0512-401 in the core of NGC1851. Our *Chandra* error circle is ∼6× smaller than the previous one from *Einstein*. Comparison to a deep *HST*/STIS FUV image shows that the $\sim 1''$ error circle now excludes all other FUV bright stars, hence providing yet stronger support for our previous identification of the faint (M_B=5.6), UV-excess ($U-B$=-0.9) Star A as the optical/UV counterpart to X 0512-401. STIS time-tag data were searched for variability on timescales from 5 min to 6 hr, but none was found, requiring a low system inclination.

The extremely low optical luminosity of Star A (confirmed here to be the only UV bright object in the accurate *Chandra* error circle), resulting in a relatively high X-ray to optical luminosity ratio, implies an ultra-compact system, where the small accretion disc provides relatively little reprocessing area. Both the similarity of the optical/UV spectral energy distributions of the counterpart in NGC6712 and Star A (Deutsch 1998; Deutsch et al. 2000), and the broad-band X-ray spectra of these sources and that in NGC6624 (Sidoli et al. 2000), further support the premise that the NGC1851 system should have a ultra-short binary period, $\lesssim$1 hr.

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